GAMMA-RAY TELESCOPES

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A–1 INTRODUCTION

Even though astronomy is one of the oldest of the experimental sciences, dating back over 5000 years, investigations in the highest frequency portions of the electromagnetic spectrum have developed only within the last two decades. Atmospheric absorption of X-rays and γ-rays prevents their direct detection and study from ground-level observatories, hence data on these energetic photons were not available until high-altitude balloons, sounding rockets, and satellites became available to place instruments above the atmosphere. In this appendix we describe the telescopes which have been developed for such observations and outline the direction of future experimentation in γ-ray astronomy.

A–2 TECHNIQUES

There is no property of the γ-ray which allows it to be detected directly. It is thus necessary to use secondaries produced by the interaction of γ-rays with some suitable target material. Heavy-metal targets because of their large atomic number Z provide large interaction cross sections. (See ch. 4.) Figure A–1 shows that for energies above 1 MeV the most important interactions of photons in heavy-metal targets are the Compton scattering process up to a crossover energy of about 10 MeV and the electron-positron pair-production above 10 MeV.[1]

The reliability with which γ-rays may be detected by these interactions depends upon the discrimination between these events and those caused by interactions of unwanted particles in the cosmic-ray environment. In fact, this consideration plays a dominant role in the design of γ-ray telescopes, since the photons must be observed above a background of 10^4 times as many charged particles. Since the consequences of the de-

[1] The crossover energy increases with decreasing atomic number becoming about 55 MeV for hydrogen (fig. 4–2).

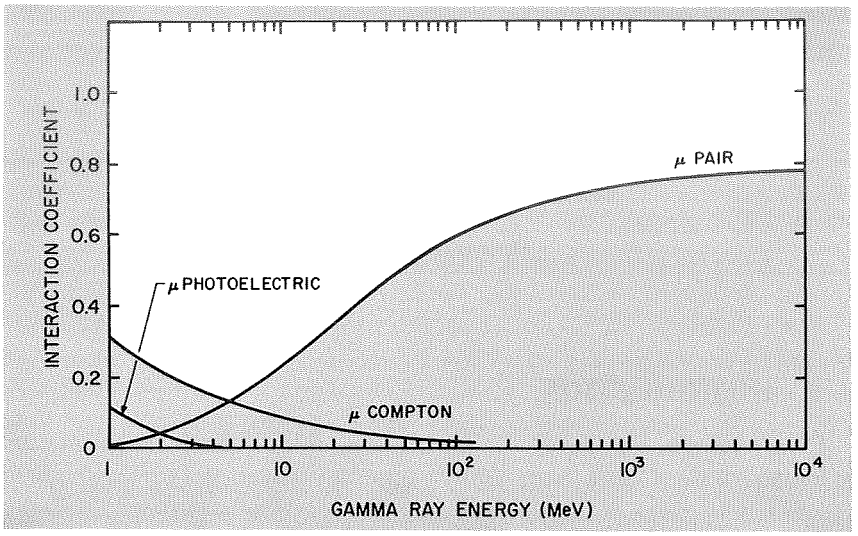

FIGURE A–1.—The interaction coefficients (proportional to cross sections) for interactions of energetic photons traversing a large atomic number ($Z=79$) medium, plotted as a function of photon energy. (For N_0 photons incident upon the material, $N=N_0e^{-\mu t}$ remain after passing through t radiation lengths of the material, where μ is the interaction coefficient; Kniffen, 1969.)

sign depend strongly on the particular objectives of the experiment, a variety of different types of detectors have been developed to search for extraterrestrial γ-rays with energies above 1 MeV. However, in each case the instrument must be able to have a reasonable detection efficiency for γ-rays with a high rejection efficiency for other types of events. In addition, it must have some degree of energy resolution and the ability to measure the arrival directions of the γ-rays in order to identify the source regions and to compare their γ-ray energy spectra with theoretical predictions, such as those presented in this monograph. The slowly varying nature of the expected continuum spectra for cosmic γ-rays above 1 MeV does not necessitate a particularly high energy-resolution for the detectors.

The telescopes currently being used in γ-ray investigations or planned for use in the near future consist of four basic types: The scintillator-Cerenkov detector telescope, pictorial-type detectors, gas Cerenkov telescopes, and ground-based night-sky Cerenkov detectors. Each of these types has its unique characteristics and advantages.

A–3 SCINTILLATOR-CERENKOV DETECTOR TELESCOPES

As the name implies, the basic element of this type of detector, as depicted in figure A–2, is a two-element telescope consisting of a scin-

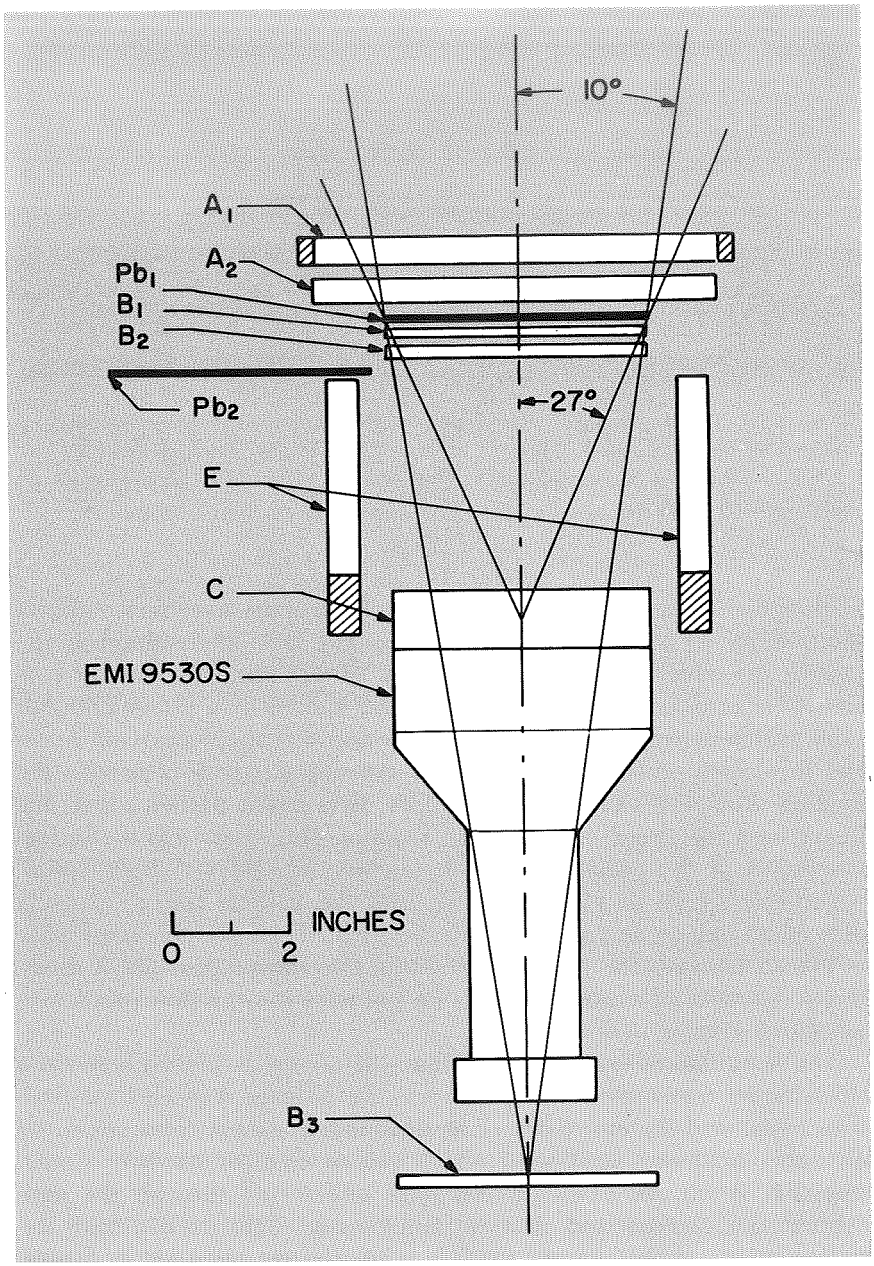

FIGURE A–2.—A schematic representation of the scintillator-Cerenkov counter of Duthie et al. (1963) with plastic scintillator anticoincidence counters, A_1, A_2, and E; a lead converter, Pb_1; scintillation counters, B_1 and B_2; and Cerenkov detector, C. The counter pairs are used for redundancy.

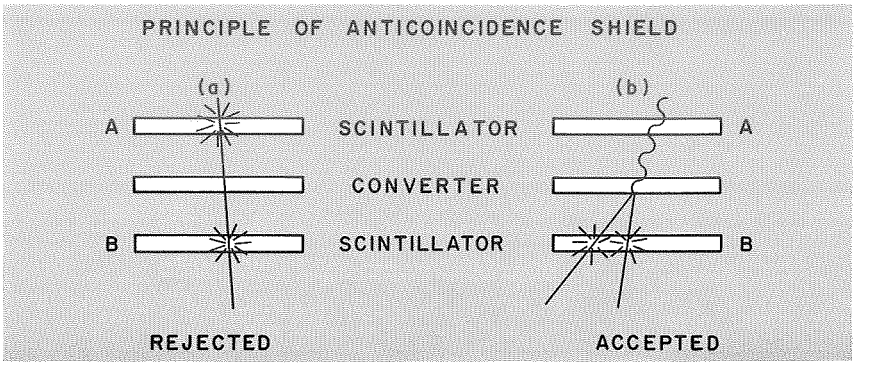

FIGURE A–3.—This figure depicts the principle of the anticoincidence shield. A charged particle (*a*) produces a flash in both scintillators A and B. The γ-ray conversion (*b*) produces two flashes in B, but none in A. Thus charged particle background events are discriminated against.

tillation counter and a Cerenkov detector. Each of these devices registers the passage of a charged particle by sensing the light emitted as the particle traverses the detecting medium. The scintillation counter consists of a translucent fluorescent material viewed by a photomultiplier tube, which converts the light flashes produced in the fluorescent material to electric pulses. The Cerenkov detector consists of a radiating medium (radiator) and a photomultiplier. Relativistic particles traveling faster than the speed of light in the radiator, c/n, where n is the refractive index of the radiator material, produce an optical "shock wave" which emits light in a forward cone with the particle trajectory as its axis and a half angle θ given by $\cos \theta = 1/\beta n$. When the photomultiplier is placed beneath the radiating medium, this device provides a directional detector which triggers only on particles moving downward with velocities greater than c/n.

The scintillator-Cerenkov coincidence telescope is placed beneath a thick target (converter) which converts the photons into electron-positron pairs; and the entire device is surrounded, except from below, by an anticoincidence scintillator which vetoes charged particle events. (See fig. A–3.) All events which pass undetected through the anticoincidence counter and provide simultaneous light flashes from the two elements of the charged particle telescope are recorded as γ-rays.

This instrument has the advantage of being relatively small, light, and simple, which makes it very useful as a space research detector. However, it has poor angular resolution and, most importantly, an inherent ambiguity in uniquely identifying weak γ-ray intensities, because of its lack of pictorial capabilities. Scintillator-Cerenkov telescopes

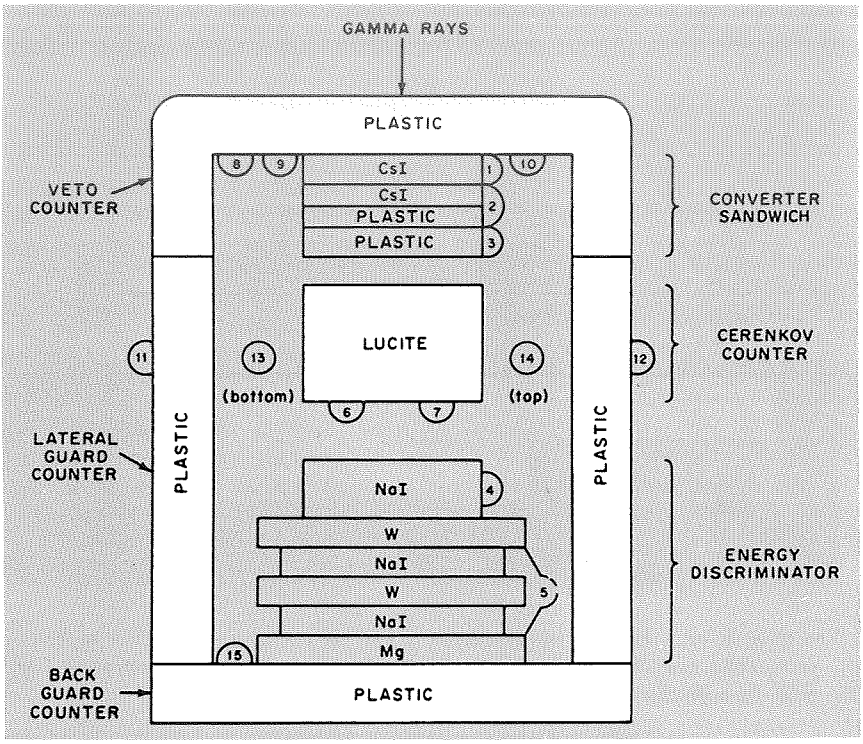

FIGURE A–4. — The OSO–3 γ-ray detector of Kraushaar et al. (1968). The principle of operation of this advanced scintillator-Cerenkov detector is discussed in the text.

have obtained very valuable data on γ-rays with energies above 50 MeV as "first-generation" γ-ray telescopes.

The counter-type detector has been used in balloon-borne experiments by Cline (1961) and Duthie et al. (1963) in search of a diffuse background intensity of cosmic γ-rays and in the satellite experiments of Kraushaar and Clark (1962) on Explorer 11; Fazio and Hafner on OSO–1 (1967); and Kraushaar, Clark, and Garmire (1968) and Valentine et al. (1970) on OSO–3. Figure A–4 is a schematic representation of the most advanced of this detector type, the OSO–3 instrument of Kraushaar et al. (1968), with a converter sandwich[2] designed to verify the electro-

[2] The converter sandwich consists of two different types of scintillators, each examined by separate photomultiplier tubes. Because cross sections for electromagnetic interactions have a different dependence on the atomic number Z than do those for nuclear interactions, the ratio of γ-ray conversions between the CsI and the plastic scintillation counters is 13:1. The expected ratio for neutrons converting to protons is 4:1.

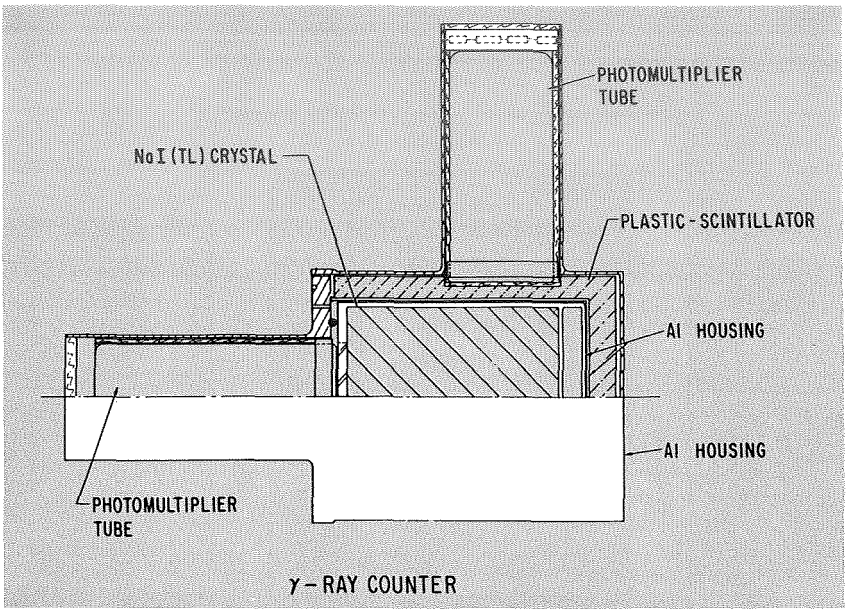

FIGURE A–5. — A schematic representation of the low-energy γ-ray counter of Peterson et al. (1968), consisting of a central totally absorbing crystal scintillator surrounded on all sides by a plastic scintillator anticoincidence counter.

magnetic nature of the suspected γ-ray events and an energy discriminator[3] to provide a crude energy measurement.

Modifications of this general type of telescope have been used in recent balloon studies of atmospheric γ-rays (Paolo, Paolo, and Constantinos, 1970) and the galactic line intensity (Sood, 1969).

The electrons and positrons produced by γ-rays below ~ 5 MeV in the converter do not have sufficient energy to penetrate both elements of the telescope; hence a different configuration is required. To detect these low-energy γ-rays, the Cerenkov element is removed and the scintillation detector is made sufficiently thick to absorb the converted electrons as their kinetic energy is lost in the scintillation material. Peterson et al. (1968) have developed such an instrument to measure the isotropic diffuse intensity of 0.25- to 6-MeV γ-rays. This detector, shown schematically in figure A–5, consists basically of a large thallium-doped sodium iodide

[3] The energy discriminator consists of alternating layers of tungsten targets, in which the incoming electron initiates an electromagnetic cascade, and scintillation counters, which measure the number of electrons existing at sample levels in the cascade. Comparison with shower theory allows a crude measurement of the energy of the incoming particles and also allows an additional discrimination against nuclear particles because of the different nature of the nuclear cascade.

crystal, surrounded on all sides by a plastic scintillator anticoincidence shield which rejects penetrating charged particles. Those γ-rays are recorded which produce high-energy electrons that are detected and totally absorbed by the crystal while no signal is recorded in the anticoincidence counter. Gamma rays in this energy range produce high-energy electrons predominately by Compton scattering rather than by pair-production. Since this scattering process destroys potential information on the direction of the incoming γ-ray, this type of detector is limited to studies of diffuse γ-ray distributions.

A-4 PICTORIAL-TYPE DETECTORS

By the early 1960's it had become clear from the results of experiments by Perlow and Kissinger (1951) and Critchfield and Ney (1952) that the primary γ-ray intensity at cosmic-ray energies is several orders of magnitude lower than the intensity of energetic charged nuclei. The many problems of identifying such a rare component in a high background led several groups to develop a variety of pictorial-type detectors in which the pair-production event could be uniquely identified and its properties studied to obtain detailed data on each of the detected γ-rays.

A-4a Nuclear Emulsions

The first pictorial detector to be used was the nuclear emulsion (Bracessi, Ceccarelli, and Salandin, 1960; Klarmann, 1962; Fichtel and Kniffen, 1965; and Frye, Reines, and Armstrong, 1965). The emulsion provides an excellent medium for the identification of the pair-production interaction, since the emulsion material serves as the conversion target as well as the detecting medium. This allows the electron pair to be observed at the point of formation, since rows of developed grains remain along the residual ion paths of the charged particles. This allows the properties of the electrons to be studied before they are modified by subsequent passage through the remainder of the converter. As a result, this medium provides a maximum of information on each detected γ-ray, with excellent determination of the energy and arrival direction of the incident photon down to a few megaelectron volts. Unfortunately, there are some very serious undesirable features of this technique which seriously limit its usefulness in γ-ray astronomy. First, it lacks time discrimination, since any γ-ray passing through the emulsion, from the time of its manufacture to the time of its development following exposure, is recorded. The resulting high background γ-ray intensity in the emulsion detector restricts its use to searches for discrete sources where its high angular resolution can be used to minimize the effect of the background. The

equation for the sensitivity of a detector for discrete source observations is given by

$$S = \frac{F_\gamma A \epsilon t}{(I_B A \epsilon t \pi \theta^2)^{1/2}} = \frac{F_\gamma}{\theta} \left(\frac{A \epsilon t}{I_B \pi} \right)^{1/2} \qquad \text{(A-1)}$$

where F_γ is the discrete γ-ray source flux, I_B the background γ-ray intensity, A the detector exposure area, ϵ the detection efficiency, t the time of exposure, and θ the angular resolution of the detector. It follows from equation (A–1) that for maximum detector sensitivity, good angular resolution is desirable, but not at the cost of a large sacrifice in background intensity. At low energies, ϵ is also a very critical parameter for emulsion detectors, since it is most tedious and time consuming to search for the low-energy electron pairs under a high-power microscope, with the resultant deterioration in accuracy and consistency. Finally, the necessity for recovery essentially limits the use of emulsions to balloon-borne experiments.

A-4b Spark Chambers

The advantages of the emulsion detector have led many experimenters to develop other types of pictorial detectors which incorporate, to as great an extent as possible, the advantages of that technique without its disadvantages. Of the other imaging detectors which might be considered for γ-ray telescopes, the spark chamber is the most advantageous for space research. A number of different approaches have been taken by experimenters in adapting this device to γ-ray observations.

Historically, the first spark chambers used in γ-ray astronomy (Cobb, Duthie, and Stewart, 1965; Frye and Smith, 1966; and Ögelman et al., 1966) incorporated the photographic readout system. In this type of device, the spark-chamber modular unit consists very simply of two parallel metal plates with a gap containing the spark gas. The gap is sufficiently large that the sparks formed in the gas between the plates can be viewed optically and recorded on film.

The first such instrument to be used in studies of extraterrestrial γ-rays with energies > 100 MeV was developed by the group under Duthie at the University of Rochester (Cobb et al., 1965). Ögelman et al. (1966) used a similar detector for studies of γ-rays above 1 GeV. In principle, this detector is similar to the counter-type detector shown in figure A–2, with sets of spark-chamber modules placed above the converter and between the scintillation and Cerenkov counters. Incoming γ-rays are converted into electron-positron pairs in the converter. As the pair electrons pass through the spark chambers the spark gas is ionized along the particle paths. When the scintillator-Cerenkov

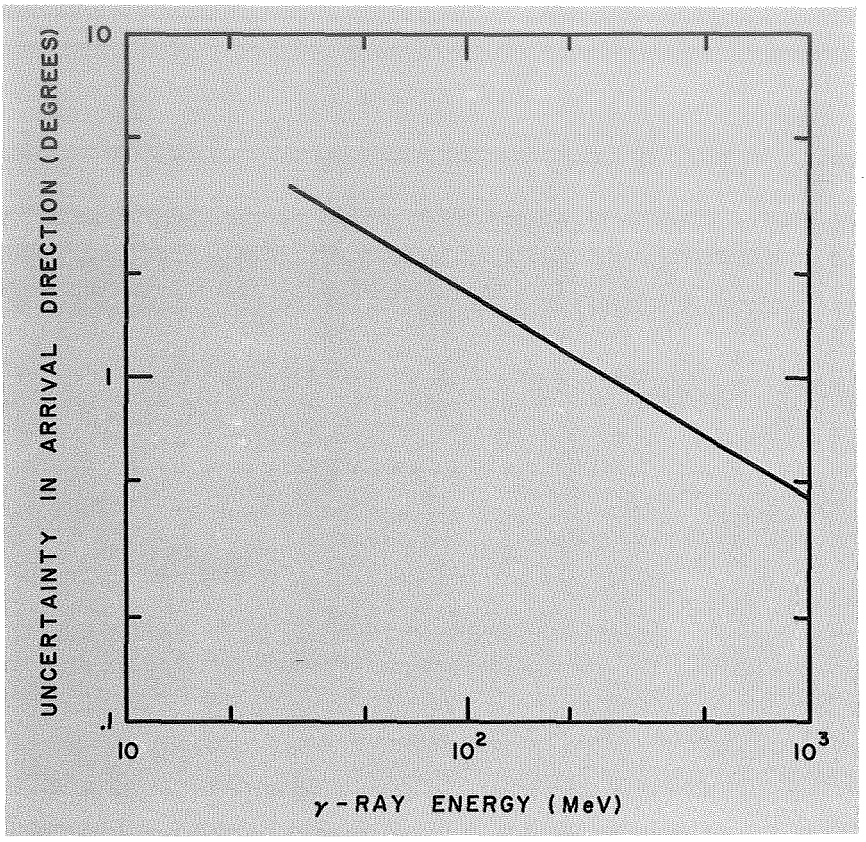

FIGURE A–6.—The one standard deviation error in determining the arrival direction of γ-rays in a typical spark chamber telescope as a function of γ-ray energy (Fichtel et al., unpublished).

telescope detects a γ-ray event, high voltage is applied across the plates, and the sparks which occur along the ion paths are recorded on photographic film. This determination of the trajectory results in a much-improved γ-ray event identification and an accurate determination of its arrival direction and maintains a wide acceptance angle. The spark chamber above the converter serves as a redundant anticoincidence indicator to prevent acceptance of charged particle events.

Frye and Smith (1966) and the group under Fichtel at Goddard Space Flight Center (Ehrmann et al., 1967) improved upon the spark chamber by distributing the converter as thin plates placed between the modules of the spark chamber. This feature provides more detail in the "picture" of the event, approaching more closely the advantages of the emulsion detector. The result is a still more reliable event identification and a more accurate determination of the γ-ray arrival direction. Figure A–6

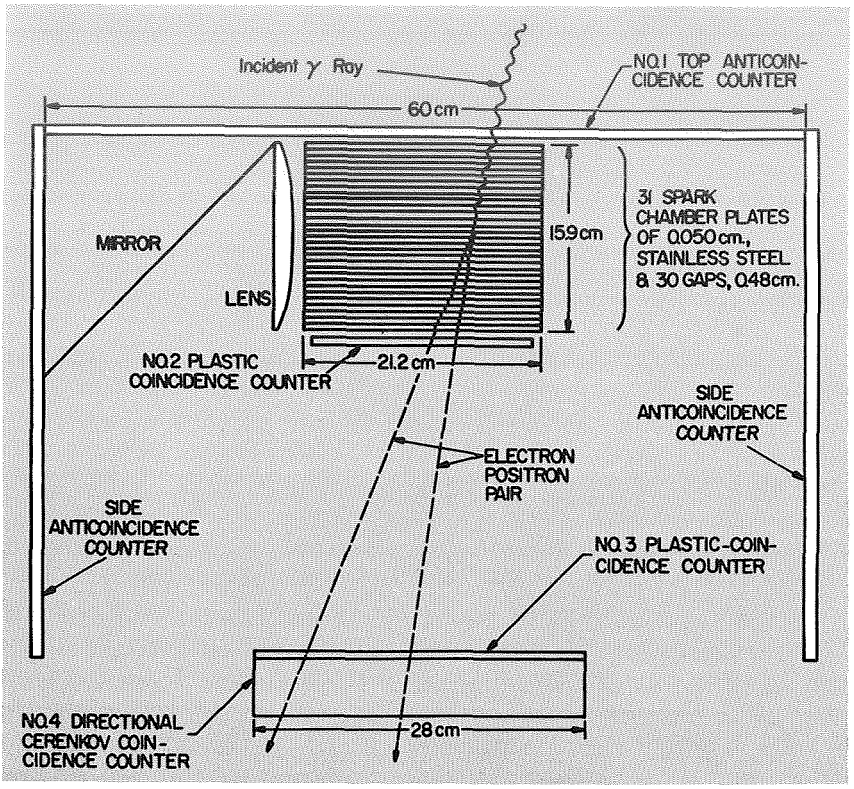

FIGURE A–7. – A recent version of the balloon-borne spark chamber γ-ray telescope of Frye et al. (1969).

shows the accuracy with which the γ-ray arrival direction can be obtained with such a configuration.

A recent version of the Case Western Reserve photographic chamber (Frye et al., 1969) is shown in figure A–7.

The balloon-borne detector of the GSFC group contains target plates between the modules beneath the scintillation counter, as shown in figure A–8. Such a configuration provides a better identification of the event, and a study of the coulomb deflections of the electrons in the plates allows a determination of the energy of each electron and hence the energy of the γ-ray (Pinkau, 1966; Kniffen, 1969). This energy information also improves the knowledge of the γ-ray arrival direction (Fichtel et al., 1969). The GSFC group (Ehrmann et al., 1967; and Ross et al., 1969) employs a ferrite core readout system consisting of a stack of spark modules. Each wire is threaded through a ferrite core and attached to a bus common to all wires of the same plane. As an event is detected and high voltage is applied across the grid, a spark breakdown

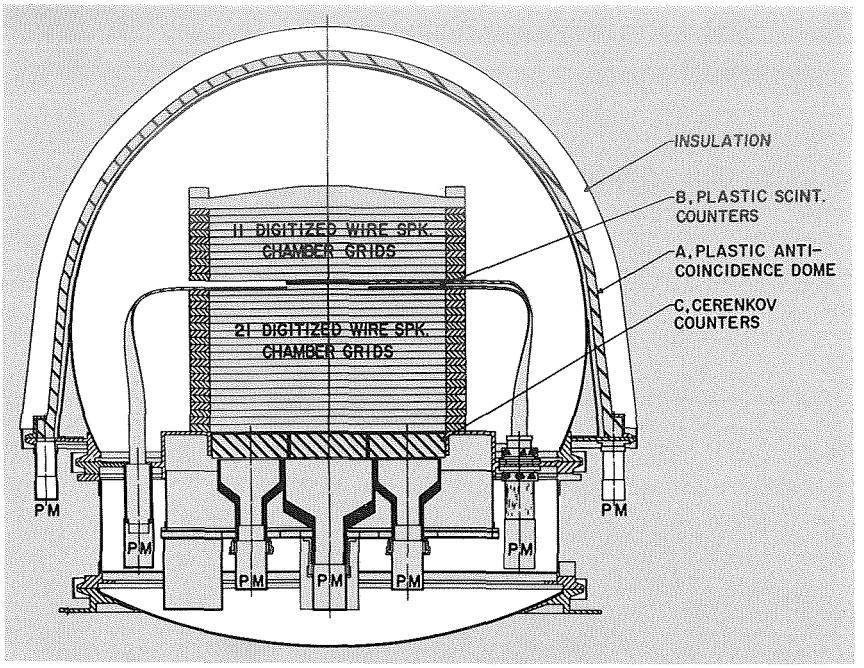

FIGURE A–8.—The ½- by ½-m digitized wire-grid spark chamber γ-ray telescope of the Goddard Space Flight Center group (Ross et al., 1969). [PM = photomultiplier tube.]

causes current to flow along the affected wires, "setting" the respective cores. Reading out the cores identifies an x and y spark location at each modular level, hence a stack of modules provides a three-dimensional "picture" of the charged particle trajectories. Figure A–9 presents a microfilm printout of such an event obtained in a balloon flight experiment. This type of readout system has the advantage that it does not require that large amounts of film be carried with the experiment, and the data can readily be transmitted to a ground-based receiving and recording station. This feature makes this system readily adaptable to a satellite configuration. Figure A–10 shows a satellite version of the telescope developed at Goddard Space Flight Center (Cline, Fichtel, and Kniffen, 1967).

Other remote readout systems have been devised for γ-ray telescopes, such as the video scanning technique developed by Fazio and Helmken (1968) for a balloon-borne detector and by a European collaboration (University of Milan; Centre d'Etudes Nucléaires de Saclay, France; Max Planck Institut für Extraterrestrische Physik, Munich) for a satellite γ-ray experiment. An acoustic readout chamber was flown by Hutchinson et al. (1970) on OGO–5.

In an attempt to improve the sensitivity of balloon-borne spark-

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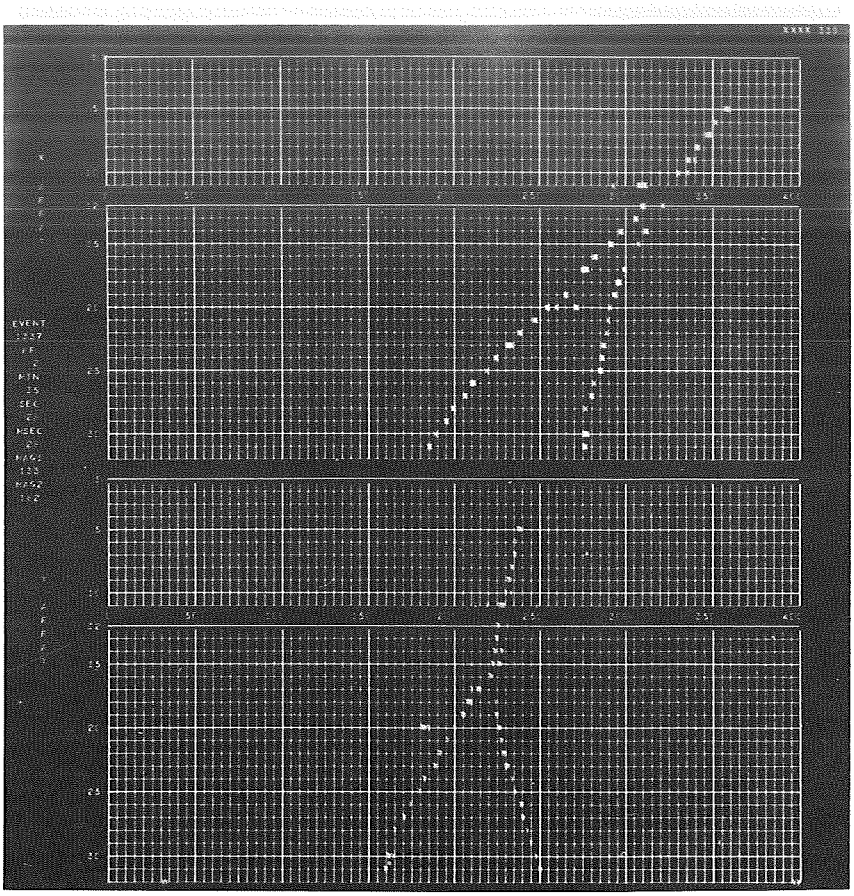

FIGURE A–9.—A computer microfilm printout of a γ-ray event observed in the spark chamber shown schematically in figure A–8. The x (top) and y (bottom) arrays represent two orthogonal views of the same pair-production event by sampling the charged particle trajectories at 32 modular or z-axis levels.

chamber telescopes for discrete source studies, May and Waddington (1969) and Share et al. (1968) have combined the excellent directional properties of nuclear emulsions with the time discrimination of spark chambers. Ross et al. (1969), Frye et al. (1969), and Board, Dean, and Ramsden (1968) have improved sensitivity by developing larger area detectors for balloon flight observations of γ-rays with energies above 30 MeV.

A xenon wide-gap spark chamber for directional studies of 1- to 100-MeV γ-rays is currently being developed by the NRL group (Kinzer et al., 1970). This device, shown in figure A–11, is a pictorial detector

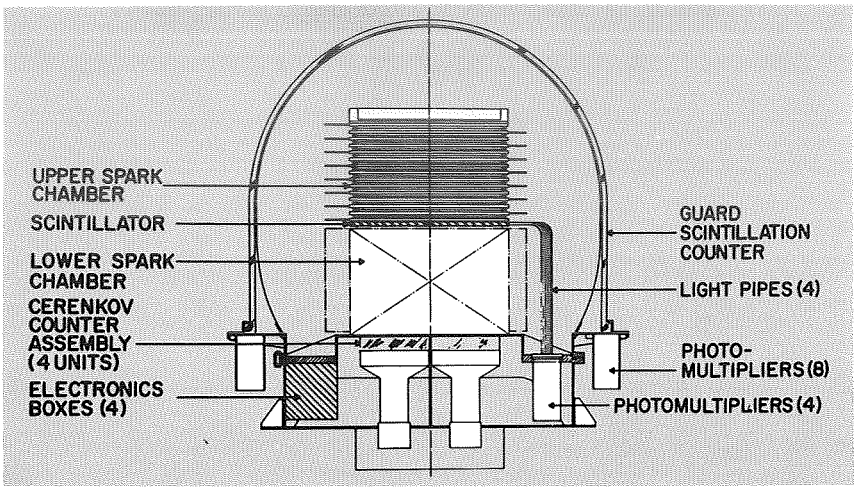

FIGURE A–10. – A schematic representation of the Goddard Space Flight Center SAS–B spark chamber γ-ray telescope (Cline, Fichtel, and Kniffen, 1967).

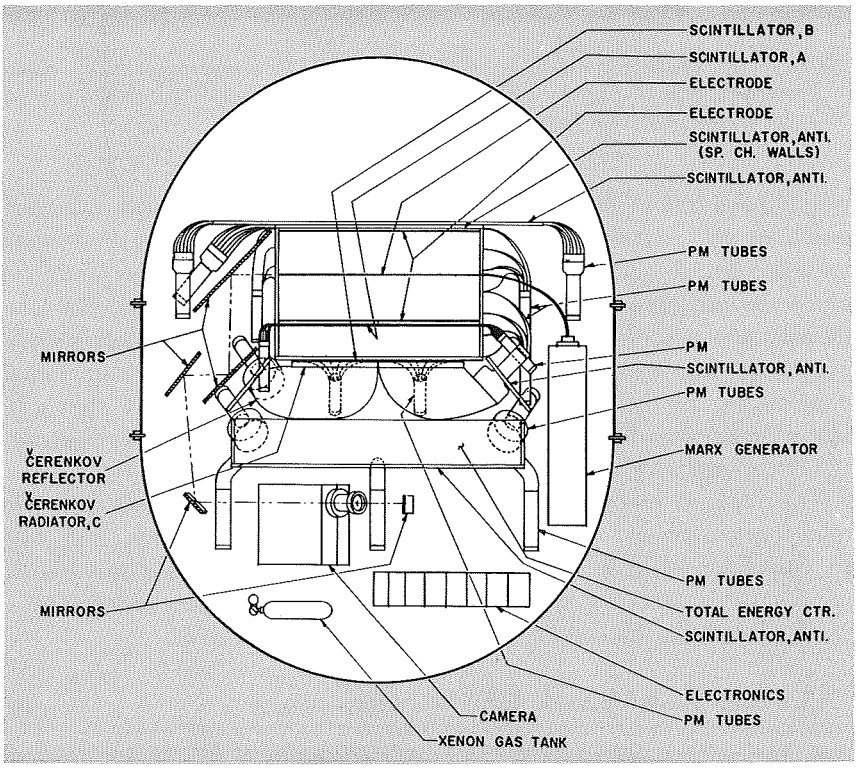

FIGURE A–11. – A schematic diagram of the NRL xenon spark chamber for 1- to 100-MeV γ-ray studies (Kinzer et al., 1970).

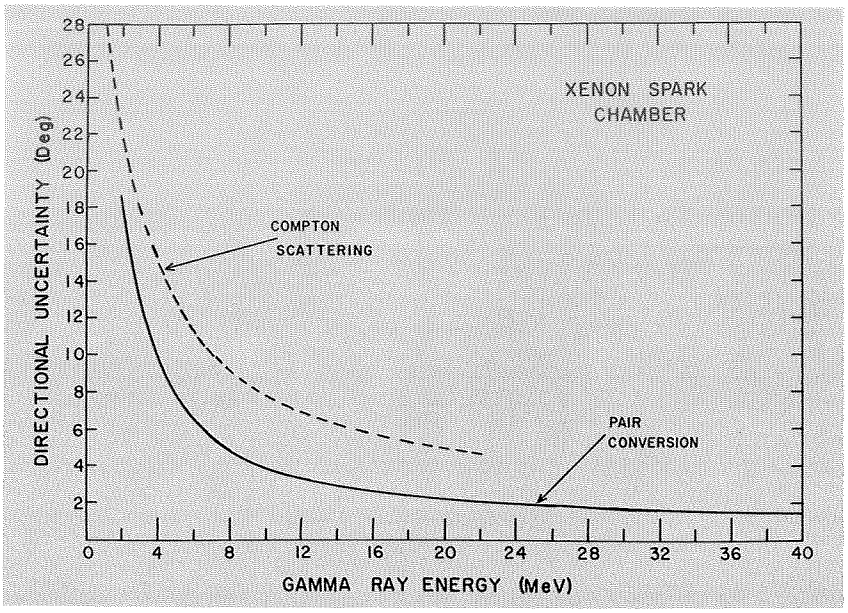

FIGURE A–12. – Root-mean-square directional uncertainty for γ-rays detected by Compton scattering and pair conversion interactions given as a function of γ-ray energy for the xenon chamber shown in figure A–11.

which uses xenon as the spark-chamber gas. Xenon, being a high-Z (large atomic number) material, acts as an effective pair-production material (ch. 4) as well as a detecting medium in which the produced electrons are photographed close to their origins. By use of the low-density gas, a sacrifice is made in conversion efficiency to obtain high-accuracy directional information. The root-mean-square directional uncertainty for the Compton scatter and pair conversion are shown in figure A–12. The detector has the additional advantage of event interpretation allowed with a "picture"-type detector.

The lack of unambiguous positive observations with balloon-borne telescopes, even with the increased accuracies and sensitivities, indicates the need for satellite detectors with sufficient energy and directional resolution to obtain a detailed map of both galactic and extragalactic γ-ray intensities as well as to observe discrete sources.

A–5 GAS CERENKOV DETECTORS

A new instrument concept has been devised by K. Greisen of Cornell University and G. Fazio of the Smithsonian Astrophysical Observatory and their collaborators for the examination of possible discrete source

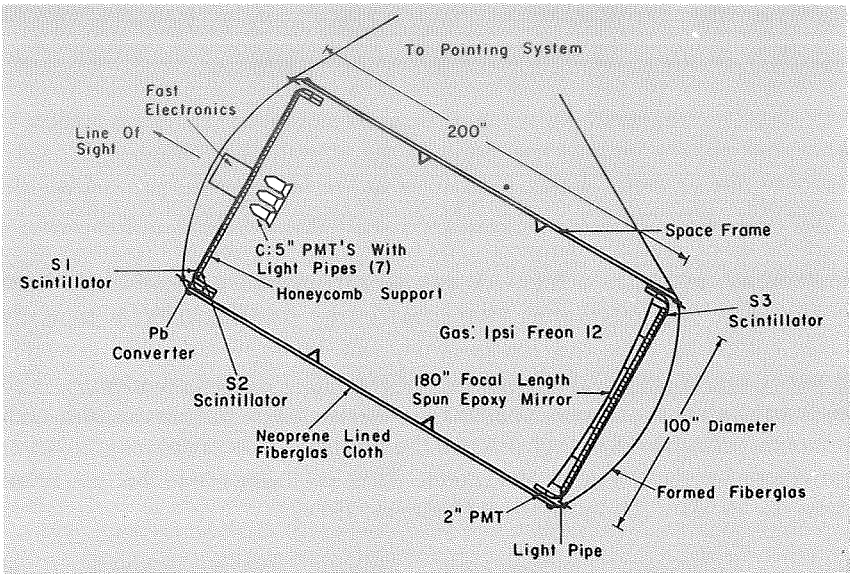

FIGURE A–13.—A schematic representation of the 100-in. telescope gas Cerenkov γ-ray detector of the Cornell and Smithsonian Astrophysical Observatory groups.

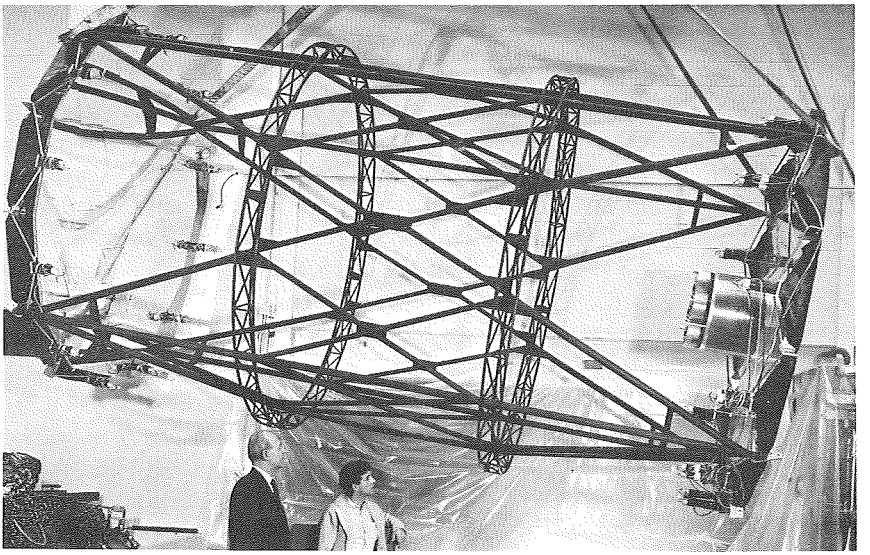

FIGURE A–14.—The 100-in.-diameter Cornell-SAO gas Cerenkov telescope. The telescope is shown pointing to the right with the mirror at the left of the picture. On the right end are the Cerenkov tubes, scintillators, and lead converter. (See fig. A–13.) The 20-ft-long instrument was designed and built at Cornell under the direction of Prof. Kenneth Greisen (shown at the bottom left with coworker Dr. Brian McBreen). (Courtesy K. Greisen.)

emitters. This instrument, depicted schematically in figure A–13 and shown in figure A–14, can be compared in principle to the scintillation-Cerenkov detector presented in figure A–2, with the solid radiator Cerenkov detector replaced by a gas Cerenkov detector. An event which is accepted passes undetected through the scintillation counter, S_1, converts to one or more charged particles in the lead converter, and is subsequently detected by a coincidence between the thin scintillator S_2 and the gas Cerenkov detector. The index of refraction of the gas is very near unity, giving it a high-velocity threshold and a small-angle light cone. Thus this detector is characterized by its simplicity, potentially large collecting area, low background, and moderate angular accuracy. A small acceptance angle limits its use to studies of discrete sources. The technique should provide excellent sensitivity for point sources, although it has the disadvantage that it lacks the unambiguous event identification provided by the imaging detectors. This technique can be extended down to 15 MeV (Helmken and Hoffman, 1970).

A–6 GROUND-BASED TELESCOPES FOR OBSERVATIONS OF 10^{11} TO 10^{12} eV γ-RAYS

Recent observations (Fazio et al., 1970a, b; Charman et al., 1970; Chatterjee et al., 1970; and Charman and Jelly, 1970) of 10^{11} to 10^{12} eV γ-rays have been made utilizing the Earth's atmosphere both as a converter and as a gas Cerenkov detector for the electrons produced by γ-rays. The background I_B in this case is the Cerenkov light produced by the isotropic background of charged particle cosmic rays, as well as starlight and other light which might appear in the night sky. This background is severe, but the small angle θ subtended by the source and the large collecting areas allow excellent sensitivities to be obtained with this type of detector.

The basic instrument is simply a large optical reflector which focuses the light onto a photoelectric device, where the detected light pulses are recorded for later analysis. Data are collected as the Earth's rotation causes the source to pass across the detector aperture, with background samples taken before and after each observation. In this observing mode, care is taken to keep the instrument stationary in order to minimize the variables encountered during the data-collection period. The high background involved makes it essential that the system be extremely stable. Observations in which the telescope is pointed at the source as it moves across the sky have also been made to increase sensitivity by increasing the observing time; but the background fluctuations involved in moving the system due to varying atmospheric depths, changing magnetic field configurations, etc., make this a most difficult mode.

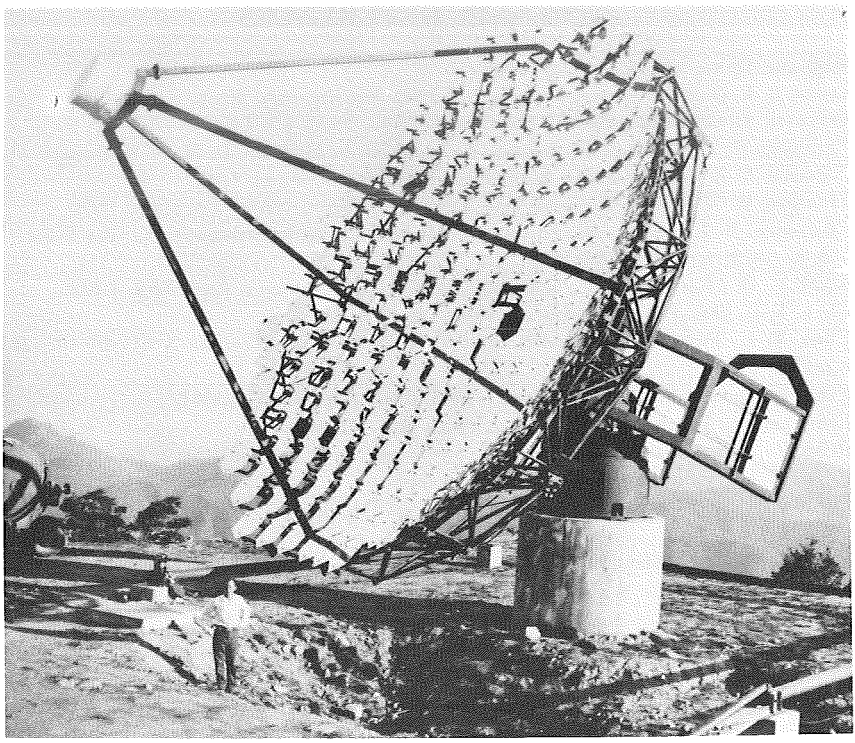

FIGURE A–15. – A picture of the 10-m reflecting night-sky Cerenkov telescope of the Smithsonian Astrophysical Observatory Mount Hopkins facility. (Courtesy G. G. Fazio.)

The 10-m telescope of the Smithsonian Astrophysical Observatory is shown in figure A–15.

A–7 SUMMARY

The detectors described in this brief survey represent the current instrumentation being used or planned for the near future in experimental γ-ray astronomy programs. Though intense effort has been put into this potentially fruitful observational field, the only unambiguous positive results obtained at this writing are the very significant results of the OSO–3 experiment of Clark, Garmire, and Kraushaar (1968) and Garmire (1970), and the ERS–18 results of Vette et al. (1970). There is a clear need for continued observations in all energy ranges with more sensitive detectors and improved techniques to map the detailed spectral and spatial structure of the celestial γ-ray distribution and to detect discrete sources and measure the characteristics of their emitted γ-radiation.